Available online at www.sciencedirect.com
ScienceDirect
Procedia CIRP 45 (2016) 243 – 246
www.elsevier.com/locate/procedia

3rd CIRP Conference on Surface Integrity (CIRP CSI)

Ultrafine-Grained Surface Layer Formation of Aluminum Alloy 5083 by Friction Stir Processing

Reza Abdi Behnagh[a,b], Ninggang Shen[a], Masoud Abdollahi[b], Hongtao Ding[a,]*

[a]*Department of Mechanical and Industrial Engineering, University of Iowa, Iowa City, Iowa 52242, USA*

[b]*Faculty of Mechanical Engineering, Urmia University of Technology, Urmia 57155-3419, Iran*

* Corresponding author. Tel.: +1-319-335-5674; Fax: +1-319-335-5669. *E-mail address:* hongtao-ding@uiowa.edu

Abstract

Friction stir processing experiments are conducted on aluminum alloy 5083 plates to enhance the surface integrity by introducing an ultrafine-grained surface layer. Microstructural analyses are carried out using optical microscopy to characterize the grain structures under various conditions. Within the produced surface layer, equiaxed ultra-fine grains are observed due to dynamic recrystallized during FSP. The grain size is reduced from 40 μm to a submicron level for the FSP rotational speed of 800 rpm. The hardness is increased to a peak value of 151 HV, which is higher than that of the unprocessed area by 50%.

Peer-review under responsibility of the scientific committee of the 3rd CIRP Conference on Surface Integrity (CIRP CSI)

Keywords: Friction stir processing; Ultra-fine grain; Surface integrity; Aluminum; Microstructure

1. Introduction

Aluminum alloy 5083 (AA 5083) is generally known for its outstanding corrosion resistance, particularly in marine environments. It is used in naval welded structures such as hulls, deck, and bulkheads, as well as in equipment items such as ladders, gratings, windows, and doors [1]. It is also the choice for superplastic aerospace and automotive parts materials.

Recently, there has been a significant research interest in generating ultra-fine grained (UFG) microstructure for aluminum alloys to enhance their strength and hardness. Severe plastic deformation (SPD) processes have been developed to obtain fine-grained microstructures for the whole workpiece of AA 5083 [2]. The UFG microstructure has been reported to be beneficial on improving ductility, formability, and mechanical strength for AA 5086 [3].

Friction stir processing (FSP) has been developed based on the principle of friction stir welding (FSW). During FSP, the rotating tool is inserted in the solid workpiece and mechanically mixes the treated surface material at elevated temperatures from the friction heat. The large process strain results in the microstructural refinement and homogenization. Thus, FSP can be implemented to locally modify the mechanical component surface for strength enhancement of AA 5083.

FSP creates an area called the ‘‘stirred zone” (SZ) or nugget zone (NZ), which corresponds to the location of the tool stirring with the heavily deformed material. Under properly controlled conditions, the microstructure of the stir zone can be refined to have equiaxed ultra-fine grains with high angle grain boundaries, which can present the ideal conditions for superplasticity in some materials [4]. The selection of process parameters is critical to optimize the process for preferable microstructure and control the amount of heat generation. Abdi Behnagh et al. [5] developed a numerical modeling framework to capture the metallo-thermo-mechanical coupling effect during a friction stirring process and predict the microstructure evolution under various process conditions. The microstructural evolution by dynamic recrystallization (DRX) was found to be dominated by the process heat generation and thermal history of the workpiece. Process parameters such as

Peer-review under responsibility of the scientific committee of the 3rd CIRP Conference on Surface Integrity (CIRP CSI)
doi:10.1016/j.procir.2016.02.062

tool rotational speed and feed rate were found to play important roles in determining the frictional heat generation, process temperature, final material mechanical properties, and microstructure.

For considering reliability and repeatability for the FSP process, it is essential to conduct a thorough experimental analysis for industrial applications. Practically, no adequate information is available in the open literature on FSP of 5083 aluminum, particularly on the effect of multi-pass FSP on the grain size achieved after the process.

In this study, the multi-pass FSP experiments are performed to investigate the process capability of microstructure refinement and strength enhancement for rolled AA 5083 plates. The microstructural characteristics of the original and processed specimens are evaluated and compared.

2. Experiments

The material used in this study was 5mm thick AA5083-H111 sheet. The chemical composition of this material is given in Table 1. The bulk material (BM) of the as-received AA5083-H111 sheet as shown in Fig. 1**Error! Reference source not found.Error! Reference source not found.** was characterized by a typical hot-rolled structure, which mostly consisted of large elongated pancake-shaped grains with length in tens of microns. The average grain size of BM was about 40 µm. The as-received rolled plates were cut into specimens of 30×10×5 mm^3 in length, width and thickness. The FSP experiments were performed on a modified vertical mill. The FSP tool made of DIN1.2436 tool steel as shown in Fig. 2 was employed in these experiments. A 3 mm tall 3.5-by-3.5 mm^2 tool tip was machined out of a concave shoulder with a diameter of 18 mm.

Table 1 Chemical composition of the experimental plates (wt. %)

Al	Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti
Balance	0.1	0.31	0.04	0.61	4.27	0.1	0.02	0.026

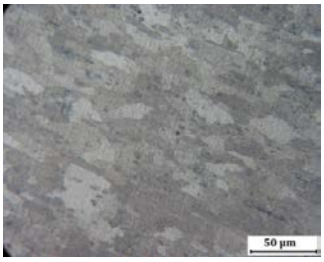

Fig. 1. Microstructure of BM.

The FSP experiment procedure is illustrated in Fig. 3. The rotating FSP tool was plunged into the AA5083-H111 sheet until the shoulder contacted the top surface of the plate; the tool was then traversed along the sheet surface. The material around the tool became softened and highly plasticized from the frictional heat generated during the process and was carried around the tool. In this study, the tool was rotated in clockwise direction with a constant tilt angle (defined as the angle between spindle and workpiece normal) of 3°, which assisted the forging action at the trailing edge of the shoulder. The tool rotational speed was varied from 600 to 1000 rpm, while its traverse speed was kept fixed at 50 mm/min. The FSP experiments were carried out at room temperature and each experimental condition was repeated three times to assure the repeatability.

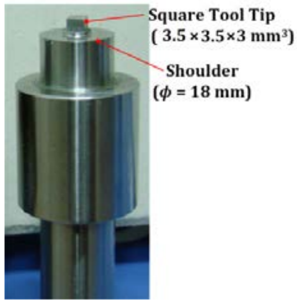

Fig. 2. FSP tool used in the experiment.

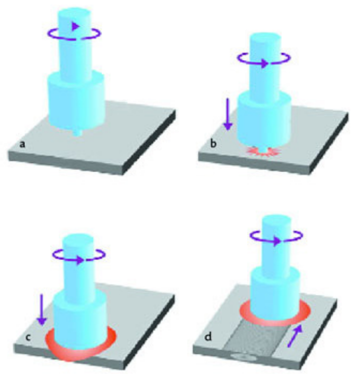

Fig. 3. The schematic of FSP.

The macro- and microstructural characteristics of the processed plate were investigated on the transverse section along the feed direction by optical microscopy (OM) under polarized light. The transverse section was polished and etched. Chemical etching was performed for one min by a modified Polltun's reagent containing 12 ml HCl, 16 ml HNO_3, 1 ml H_2O, 1 ml HF, and 12 ml of a solution consisting of 3g chromic acid per 10 ml H_2O at 25°C. Grain size measurement was carried out using the line intercept method. The hardness profile was obtained along the cross section of samples by a Vickers microhardness tester using a load of 100 gf for a dwell time of 5 seconds.

3. Results and Discussions

Fig. 4 shows the surface appearance of one of the FSPed 5083 alloy of 300 mm in length. AS and RS are referred to the advancing side and retreating side of the tool rotation, respectively. The top surface is very flat and smooth in spite of the tool's stirring. The surface was free of cracks or any other visible defects with only feed marks from the tool feeding motion.

Fig. 4. The top surface after FSP

A metallographic cross section for the FSP of AA 5083 is shown in Fig. 5. The metallographic section showed a classic friction stir weld nugget region and the stirring marks. The width of the nugget inferred from Fig. 5 was around 5 mm which was close to the tool pin diameter. Intense plastic deformation and frictional heating during FSP resulted in the generation of a recrystallized fine-grained structure within the nugget zone (NZ), which agreed well with the previous study of microstructure evolution during FSP [6,7].

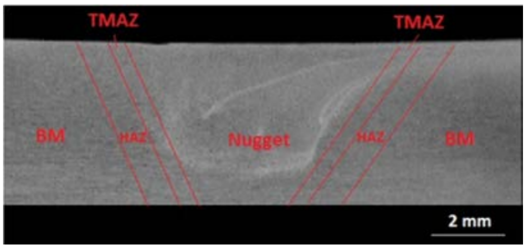

Fig. 5. Optical microscopy image of FSP sample.

Error! Reference source not found. Fig. 6 shows the different microstructural zones of FSPed sample. Fine, equiaxed grains can be observed in NZ, which was formed due to the dynamic recrystallization process as a result of the huge amount of heat generation during FSP. As can be seen in **Error! Reference source not found.**b, the recrystallized grains were equiaxed, similar in size and uniformly distributed. The average grain size of FSPed sample was around 1 µm, at a tool rotational speed of 800 rpm. Various FSP parameters, such as tool geometry and rotational speed, affect the recrystallization process in the nugget zone. The recrystallization could be more pronounced by increasing either the number of passes or the ratio of the tool rotation/traverse speed [8]. The transition region between NZ and BM was denoted as the thermo-mechanically affected zone (TMAZ), where the original elongated grains from the as-received material were deformed in an upward flowing pattern around the NZ as shown in **Error! Reference source not found.**c. A smooth transition can be found in terms of both grain size and grain orientation from BM to NZ.

The effect of rotational speed on the microstructure change was investigated in terms of grain size and hardness. The histogram of average grain size, average and maximum hardness values for each rotational speed are shown in Fig. 7. The grain size data was obtained from the NZ of each sample, where the maximum hardness values were achieved. In order to examine the property variations across the FSPed region, the horizontal hardness profiles were obtained at the top surface and 2 mm deep from the top surface of each sample. As shown in Fig. 8, hardness enhancements at the top surface and 2 mm below are quite similar. From Figs. 7 and 8, it was clear that at the rotational speed of 800 rpm, the hardness was increased to the maximum value of 151 HV, which is harder than that of the unprocessed area by 50%, and the grain size was refined to a submicron level. The increase in hardness can be attributed to the significant grain refinement of the initial untreated structure to the fine grains according to the well-known Hall-Petch equation [9]. Very fine equiaxed grains were observed in the NZ due to the dynamic recovery (DRV), geometric dynamic recrystallization (GDRX), and discontinuous dynamic recrystallization (DDRX) acting during FSP [10]. This refined and equiaxed grain structure improves the formability and super-plastic behavior and enhances the hardness and strength [11]. On one hand, decreasing the rotational speed from 800 rpm to 600 rpm resulted in less friction heat generation for the dynamic recrystallization process, which produced a larger grain size of about 3 microns and lower hardness as can be seen in Fig. 7. On the other hand, increasing the rotational speed to 1000 rpm generated more heat during the FSP process and hence, the newly recrystallized grains started to grow. The resultant grain size was about 4 µm for 1000 rpm condition. The results showed that the specimens produced at the rotational speed of 800 rpm show the finest grains. In all, the rotational speed of 800 rpm was found to have the best properties in terms of fine grain structure and strength enhancement within the tested experimental conditions in this study.

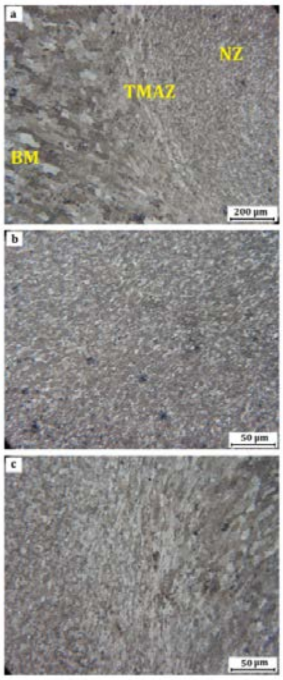

Fig. 6. Optical microscopy images for: (a) different areas formed during the process; (b) NZ; (c) TMAZ.

Furthermore, higher hardness values were observed at the advancing side (AS) at 2 mm below the surface in the processed zone, due to the smaller grain size compared with the retreating side (RS). Indeed, the AS achieved higher levels of deformation and temperature during the process, which allowed a higher recrystallization potential, and so, a more severe grain refinement [12]. As a result, as can be seen in Fig. 8b, by increasing the distance from the center of the specimen to the edges, the hardness values in AS are higher than that in RS.

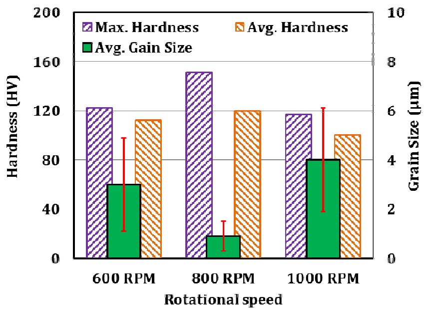

Fig. 7. Histograms of maximum hardness, average hardness and average grain size for each sample.

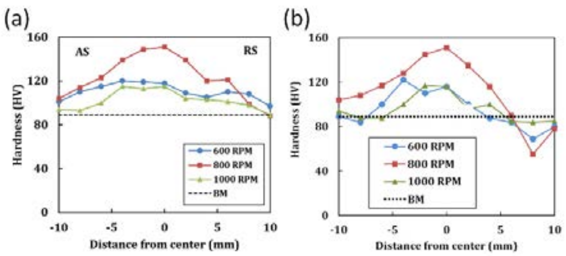

Fig. 8. Microhardness measurements (a) top surface (b) 2 mm from the top surface

4. Conclusions

In this study, friction stir processing experiments were performed on a simple milling machine system to investigate the effects of surface modification for AA 5083. The experimental results showed a significant surface enhancement for AA 5083 in terms of both microstructural refinement and mechanical strength improvement. Remarkable microstructural homogenization and grain refinement were induced after the one-pass FSP by properly selection of operation parameters. FSP at rotational speed of 800 rpm and transverse speed of 50 mm/min produced grains less than 1 µm within a subsurface region of 5 mm in width and 3 mm in depth. A 50% increase in the surface hardness was achieved due to grain refinement after FSP. Increasing or decreasing the rotational speed resulted in coarser grain sizes and less strength enhancement.

References

[1] Babu, N., Karunakaran, N., Balasubramanian, V., 2015, A study to estimate the tensile strength of friction stir welded AA 5059 aluminium alloy joints, The International Journal of Advanced Manufacturing Technology, DOI:10.1007/s00170-015-7391-9.

[2] Sakai, G., Horita, Z., Langdon, T. G., 2005, Grain refinement and superplasticity in an aluminum alloy processed by high-pressure torsion, Materials Science and Engineering: A, 393/1,2:344–351, DOI:10.1016/j.msea.2004.11.007.

[3] Ramesh, K. N., Pradeep, S., Pancholi, V., 2012, Multipass Friction-Stir Processing and its Effect on Mechanical Properties of Aluminum Alloy 5086, Metallurgical and Materials Transactions A, 43/11:4311–4319, DOI:10.1007/s11661-012-1232-3.

[4] El-Danaf, E. A., El-Rayes, M. M., Soliman, M. S., 2010, Friction stir processing: An effective technique to refine grain structure and enhance ductility, Materials & Design, 31/3:1231–1236, DOI:10.1016/j.matdes.2009.09.025.

[5] Abdi Behnagh, R., Shen, N., Ansari, M. A., Narvan, M., Besharati Givi, M. K., et al., 2015, Experimental Analysis and Microstructure Modeling of Friction Stir Extrusion of Magnesium Chips, Journal of Manufacturing Science and Engineering, 138/4:041008, DOI:10.1115/1.4031281.

[6] Shahraki, S., Khorasani, S., Abdi Behnagh, R., Fotouhi, Y., Bisadi, H., 2013, Producing of AA5083/ZrO2 Nanocomposite by Friction Stir Processing (FSP), Metallurgical and Materials Transactions B, 44/6:1546–1553, DOI:10.1007/s11663-013-9914-9.

[7] Ansari, M. A., Behnagh, R. A., Narvan, M., Naeini, E., Givi, M., et al., 2015, Optimization of Friction Stir Extrusion (FSE) Parameters Through Taguchi Technique, Transactions of the Indian Institute of Metals, pp. 1–7, DOI:10.1007/s12666-015-0686-6.

[8] Surekha, K., Murty, B. S., Rao, K. P., 2008, Microstructural characterization and corrosion behavior of multipass friction stir processed AA2219 aluminium alloy, Surface and Coatings Technology, 202/17:4057–4068, DOI:10.1016/j.surfcoat.2008.02.001.

[9] Behnagh, R. A., Besharati Givi, M. K., Akbari, M., 2012, Mechanical Properties, Corrosion Resistance, and Microstructural Changes during Friction Stir Processing of 5083 Aluminum Rolled Plates, Materials and Manufacturing Processes, 27/6:636–640, DOI:10.1080/10426914.2011.593243.

[10] McNelley, T. R., Swaminathan, S., Su, J. Q., 2008, Recrystallization mechanisms during friction stir welding/processing of aluminum alloys, Scripta Materialia, 58/5:349–354, DOI:10.1016/j.scriptamat.2007.09.064.

[11] Darras, B. M., Khraisheh, M. K., Abu-Farha, F. K., Omar, M. A., 2007, Friction stir processing of commercial AZ31 magnesium alloy, Journal of Materials Processing Technology, 191/1–/3:77–81, DOI:10.1016/j.jmatprotec.2007.03.045.

[12] Sato, Y. S., Nelson, T. W., Sterling, C. J., Steel, R. J., Pettersson, C.-O., 2005, Microstructure and mechanical properties of friction stir welded SAF 2507 super duplex stainless steel, Materials Science and Engineering: A, 397/1–/2:376–384, DOI:10.1016/j.msea.2005.02.054.